Engineering Science and Technology, an International Journal 19 (2016) 113–134

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Engineering Science and Technology, an International Journal

journal homepage: http://www.elsevier.com/locate/jestch

Full Length Article

Automatic generation control of multi-area power systems with diverse energy sources using Teaching Learning Based Optimization algorithm

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ARTICLE INFO

Article history:
Received 18 May 2015
Received in revised form
13 July 2015
Accepted 20 July 2015
Available online 14 August 2015

Keywords:
Automatic Generation Control (AGC)
Boiler dynamics
Teaching Learning Based Optimization (TLBO) algorithm
Generation Rate Constraint (GRC)
Governor Dead Band (GDB)
Proportional-Integral-Double Derivative (PIDD) controller

ABSTRACT

This paper presents the design and analysis of Proportional-Integral-Double Derivative (PIDD) controller for Automatic Generation Control (AGC) of multi-area power systems with diverse energy sources using Teaching Learning Based Optimization (TLBO) algorithm. At first, a two-area reheat thermal power system with appropriate Generation Rate Constraint (GRC) is considered. The design problem is formulated as an optimization problem and TLBO is employed to optimize the parameters of the PIDD controller. The superiority of the proposed TLBO based PIDD controller has been demonstrated by comparing the results with recently published optimization technique such as hybrid Firefly Algorithm and Pattern Search (hFA-PS), Firefly Algorithm (FA), Bacteria Foraging Optimization Algorithm (BFOA), Genetic Algorithm (GA) and conventional Ziegler Nichols (ZN) for the same interconnected power system. Also, the proposed approach has been extended to two-area power system with diverse sources of generation like thermal, hydro, wind and diesel units. The system model includes boiler dynamics, GRC and Governor Dead Band (GDB) non-linearity. It is observed from simulation results that the performance of the proposed approach provides better dynamic responses by comparing the results with recently published in the literature. Further, the study is extended to a three unequal-area thermal power system with different controllers in each area and the results are compared with published FA optimized PID controller for the same system under study. Finally, sensitivity analysis is performed by varying the system parameters and operating load conditions in the range of ±25% from their nominal values to test the robustness.

1. Introduction

Automatic Generation Control (AGC) plays an important role in the large scale multi-area interconnected power systems to maintain system frequency and tie-line powers at their nominal values. Due to sudden disturbances or some other reasons if the generated active power becomes less than the power demand, the frequency of generating units tends to decrease and vice versa [1,2]. This causes the system frequency to deviate from its nominal value which is undesirable. To damp out the frequency deviation quickly and to keep the tie-line power at its scheduled value, AGC concept is used. However, the constant frequency cannot be obtained by the speed governor alone. So, a control system is essential to cancel the effects of the sudden load changes and to keep the frequency at the nominal value [3–5].

Over the past decades, the researchers in the world over are trying to understand the AGC problem using several control strategies and optimization techniques and the database is scanty. The concepts of optimal control theory [6], Integral [7], Proportional-Integral [8], Proportional-Integral-Derivative [9], Integral-Double Derivative [10], Fractional Order PID [11] and Proportional-Integral-Double Derivative [12] have been applied and their performance has been compared for an AGC problem. Daneshfar and Bervani [13] have suggested the multi-objective optimization problem (MOP) approach and Genetic Algorithm (GA) technique is used to tuned PI controllers for multi-area power systems. Gozde et al. [14] have used Artificial Bee Colony (ABC) optimization technique to study the dynamic performance of AGC in a two-area interconnected thermal power system. Ali and Abd Elazim [15] have optimized the gains of PID controller using BFOA technique for LFC problem and they have compared it with Ziegler Nichols (ZN) and GA optimization techniques. Dash et al. [16] have the applied cuckoo search algorithm for AGC of a three-area thermal system with single reheat turbine considering Generation Rate Constraints. Mohanty et al. [17] have applied Differential Evolution (DE) algorithm based PID controller for multi-area multi-source power system. Recently, Sahu et al. [18] have applied hybrid firefly algorithm and pattern search optimization technique with PID controller in AGC problem. It is

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Peer review under responsibility of Karabuk University.

http://dx.doi.org/10.1016/j.jestch.2015.07.011

observed from literature survey that, most of the work was confined to reheat thermal plants, hydro plants and relatively lesser attention has been devoted to wind, diesel generating units. As conventional sources are exhausting day by day, now it is essential to make use of non-conventional sources such as solar and wind energy at favorable locations [19].

It is clear from literature survey that the performance of the power system depends on the controller structure and the optimization techniques employed to optimize the controller parameters. Classical techniques of determining the optimum gains of the controllers may fail to give optimal solution while solving harder constrained problems with large number of variables or in a large search space. To overcome such difficulties evolutionary algorithms (EAs) are used for searching near-optimum solutions to problems. Hence, proposing and implementing new controller approaches using high performance heuristic optimization algorithms to real world problems are always welcome.

In this proposed work optimum values of PIDD controller gains are obtained by using Teaching Learning Based Optimization (TLBO) algorithm. The performance of many optimization techniques depends on proper selection of certain control parameters. In Particle Swarm Optimization (PSO) algorithm the control parameters influencing performance are inertia weight (w), social and cognitive parameters (c_1 and c_2 respectively), in Differential Evolution (DE) algorithm the control parameters are scale factor (F) and crossover rate (CR). Selection of these parameters plays a very crucial role in the performance of the algorithms. However TLBO algorithm does not require any controlling parameter. Since it is a parameter free algorithm, it is simple, effective and faster which motivates many researchers to use this algorithm in their own research area. TLBO algorithm proposed by Rao et al. [20] is a recently developed evolutionary optimization technique which does not require any control parameter.

Having known all this, in the present work, it is planned to carry out a methodical simulation study, to evaluate the performance of the proposed PIDD controller with TLBO algorithm. Simulation results are compared with some recently published works based on Firefly Algorithm (FA) [18], hybrid Firefly Algorithm and Pattern Search (hFA-PS) algorithm [18], Bacteria Foraging Optimization Algorithm (BFOA) [15], Genetic Algorithm (GA) [15] and conventional Ziegler Nichols (ZN) [15]. It is observed that TLBO optimized PIDD controller for the proposed two-area power system gives better dynamic performance in terms of settling time, overshoot and undershoot. In addition the proposed approach is extended to multi-area multi-source power systems. The better system performance is achieved with TLBO optimized PIDD controller compared to others. Further a three unequal-area thermal power system is considered. Results obtained are compared with that of a recently published work proposed by Padhan et al. [21]. Robustness test is performed by varying the operating load condition and system parameters in the range of ±25% from their nominal values.

2. Materials and methods

2.1. Two-area power system model

A two-area non-reheat interconnected thermal power system as shown in Fig. 1 is considered. Each area has a rating of 2000 MW with a nominal load of 1000 MW. The system is widely used in literature for the design and analysis of AGC [8,15,22]. In Fig. 1, B_1 and B_2 are the frequency bias parameters; ACE_1 and ACE_2 are area control errors; u_1 and u_2 are the control outputs from the controller; R_1 and R_2 are the governor speed regulation parameters in p.u. Hz; T_{G1} and T_{G2} are the speed governor time constants in seconds; ΔP_{G1} and ΔP_{G2} are the governor output command (p.u.); T_{T1} and T_{T2} are the turbine time constant in seconds; ΔP_{T1} and ΔP_{T2} are the change in turbine output powers; ΔP_{D1} and ΔP_{D2} are the load demand changes; K_{P1} and K_{P2} are the power system gains; T_{P1} and T_{P2} are the power system time constant in seconds; T_{12} is the synchronizing coefficient in p.u.; ΔP_{Tie} is the incremental change in tie line power (p.u.); ΔF_1 and ΔF_2 are the system frequency deviations in Hz. The relevant parameters are given in Appendix A.

2.2. Controller structure and objective function

Classical PID controllers are used in most of the industrial processes due to their simple and robust design, low cost, and effectiveness for linear systems. However, the classical PID controllers are usually not effective due to their linear structure, especially, if the processes involved are higher order, time delay systems and

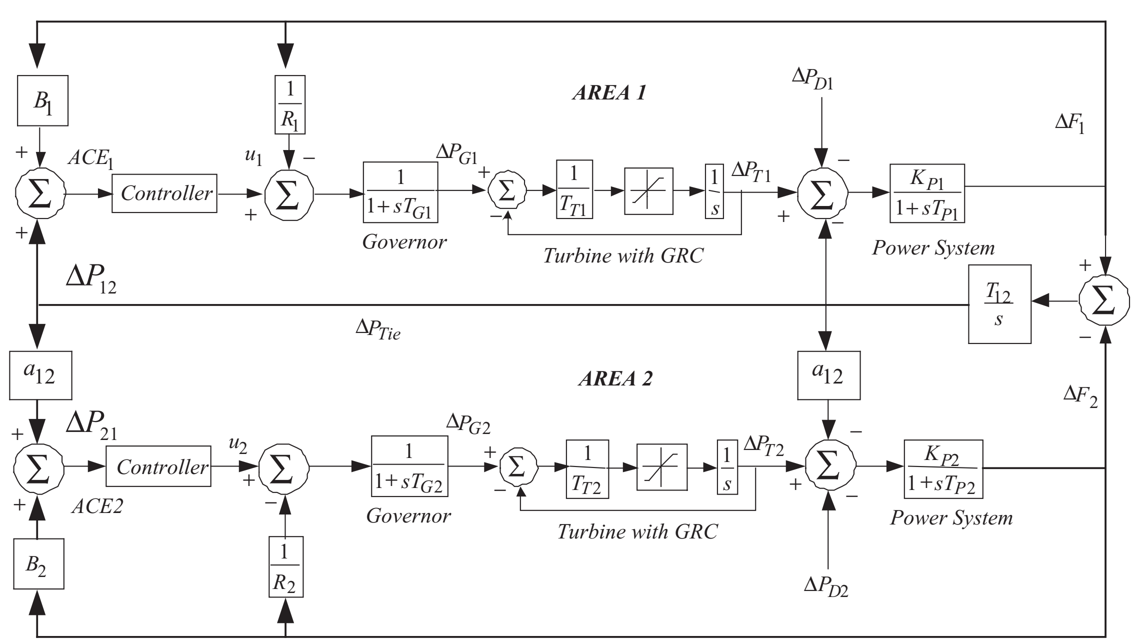

Fig. 1. Transfer function model of two-area non-reheat thermal power system.

systems with uncertainties. On the other hand Proportional-Integral-Double Derivative (PIDD) controller improves the stability of the system and helps to achieve better settling time compared to PID controller [12]. In view of the above, PIDD controllers are chosen in this paper to solve the AGC problem.

In view of the fact that investigation has been carried out on a two-equal area non-reheat turbine thermal power system, similar kinds of PIDD controllers are considered in both areas. The design of PIDD controller requires determination of the three main parameters: Proportional gain (K_P), Integral gain (K_I) and Double Derivative time constant gain (K_{DD}). The transfer function of PIDD controller is given by Equation (1)

$$TF_{PIDD} = K_P + \frac{K_I}{s} + K_{DD}s^2 \tag{1}$$

The error inputs to the controllers are the respective Area Control Errors (ACE) given by:

$$e_1(t) = ACE_1 = B_1\Delta F_1 + \Delta P_{12} \tag{2}$$

$$e_2(t) = ACE_2 = B_2\Delta F_2 + \Delta P_{21} \tag{3}$$

where ΔP_{Tie} is the change in tie-line power. When the system is subjected to a small disturbance, ACEs are used as actuating signal to reduce ΔP_{Tie} and ΔF to zero when steady state is reached.

In the design of a modern heuristic optimization technique based controller, the objective function is first defined based on the desired specifications and constraints. Performance criteria usually considered in the control design are the Integral of Time multiplied Absolute Error (ITAE), Integral of Squared Error (ISE), Integral of Time multiplied Squared Error (ITSE) and Integral of Absolute Error (IAE). ITAE criterion reduces the settling time which cannot be achieved with IAE or ISE based tuning. ITAE criterion also reduces the peak overshoot. ITSE based controller provides large controller output for a sudden change in set point which is not advantageous from controller design point of view. It has been reported that ITAE is a better objective function in LFC studies [22,23]. Therefore in this paper ITAE is used as objective function to optimize the gains of IDD/PIDD controller. Expression for the ITAE objective function is shown in Equation (4).

$$J = ITAE = \int_0^{t_{sim}} (|\Delta F_i| + |\Delta P_{Tie-i-k}|) \cdot t \cdot dt \tag{4}$$

In the above equations, ΔF_i is the incremental change in frequency of area i; $\Delta P_{Tie-i-k}$ is the incremental change in tie line power connecting between area i and area k; t_{sim} is the time range of simulation.

3. Teaching Learning Based Optimization (TLBO) algorithm

Teaching Learning Based Optimization (TLBO) algorithm [20,24] was introduced by Rao et al. Since then this algorithm has become a very popular and powerful optimization algorithm that is applied in many engineering fields. The working process of TLBO consists of two parts (i) Teacher Phase and (ii) Learner Phase. In teacher phase students (learners) learn from teachers and in learner phase students learn through interaction between learners (students). Different steps involved in TLBO algorithm [20] are presented below.

3.1. Initialization

In this step the initial population of size $[NP \times D]$ is randomly generated, where NP indicates size of population i.e. number of learners and D indicates the dimension of the problem i.e. number of subjects offered. The i^{th} column of the initial population represents the marks secured by different learners in the i^{th} subject.

$$\text{Initial population } X = \begin{bmatrix} x_{1,1} & x_{1,2} & \dots & x_{1,D} \\ x_{2,1} & x_{2,2} & \dots & x_{2,D} \\ . & . & & . \\ . & . & & . \\ x_{NP,1} & x_{NP,2} & \dots & x_{NP,D} \end{bmatrix} \tag{5}$$

3.2. Teacher phase

In this phase each teacher tries to improve the mean result of a class in the subject assigned to him. As the teacher trains the learners he is assumed to be a highly learned person and taken as the best learner i.e. the best solution X_{best} is identified and assigned as teacher. The mean value of each column i.e. the mean value of the marks obtained by different students for each subject is calculated as:

$$M_d = [m_1, m_2, \dots\dots, m_D] \tag{6}$$

The difference between the mean results in a particular subject and the result of corresponding teacher is given by

$$M_{diff} = rand(0,1)[X_{best} - T_F M_d] \tag{7}$$

where T_F is the teaching factor and $rand(0,1)$ is a random number between 0 and 1. Value of T_F is taken as either 1 or 2 and decided randomly using the equation given below:

$$T_F = round[1 + rand(0,1)] \tag{8}$$

The existing population is updated by the expression:

$$X_{new} = X + M_{diff} \tag{9}$$

Elements of X_{new} are accepted if $f(X_{new}) < f(X)$; otherwise elements of X are accepted.

4. Simulation results and discussion

4.1. Implementation of TLBO algorithm

The model of the system under study is developed in MATLAB/SIMULINK environment and the TLBO program is written (in .mfile). The developed model is simulated in a separate program (by .mfile) considering a 5% step load increase in area-1. The objective function is determined in the .mfile and used in optimization algorithm. A series of experiments was conducted to properly choose the population size and number of iterations of TLBO algorithm. In the present study, a population size of $NP = 50$ and the maximum number of iterations are taken as 100. For the very first execution of the program, wider solution space can be given, and after getting the solution, one can shorten the solution space nearer to the values obtained in the previous iterations. Simulations were conducted on an Intel, Core i-5 CPU of 2.5 GHz, 8 GB, 64-bit processor computer in the MATLAB 7.10.0.499 (R2010a) environment. The flow chart of proposed TLBO approach is shown in Fig. 2. The optimization was repeated 50 times and the best final solution among the 50 runs is chosen as final controller parameters. The best final solutions of controller parameters are shown in Table 1.

4.2. Analysis of results

The effectiveness of proposed TLBO tuned PIDD controller is compared with TLBO optimized IDD controller and other recently

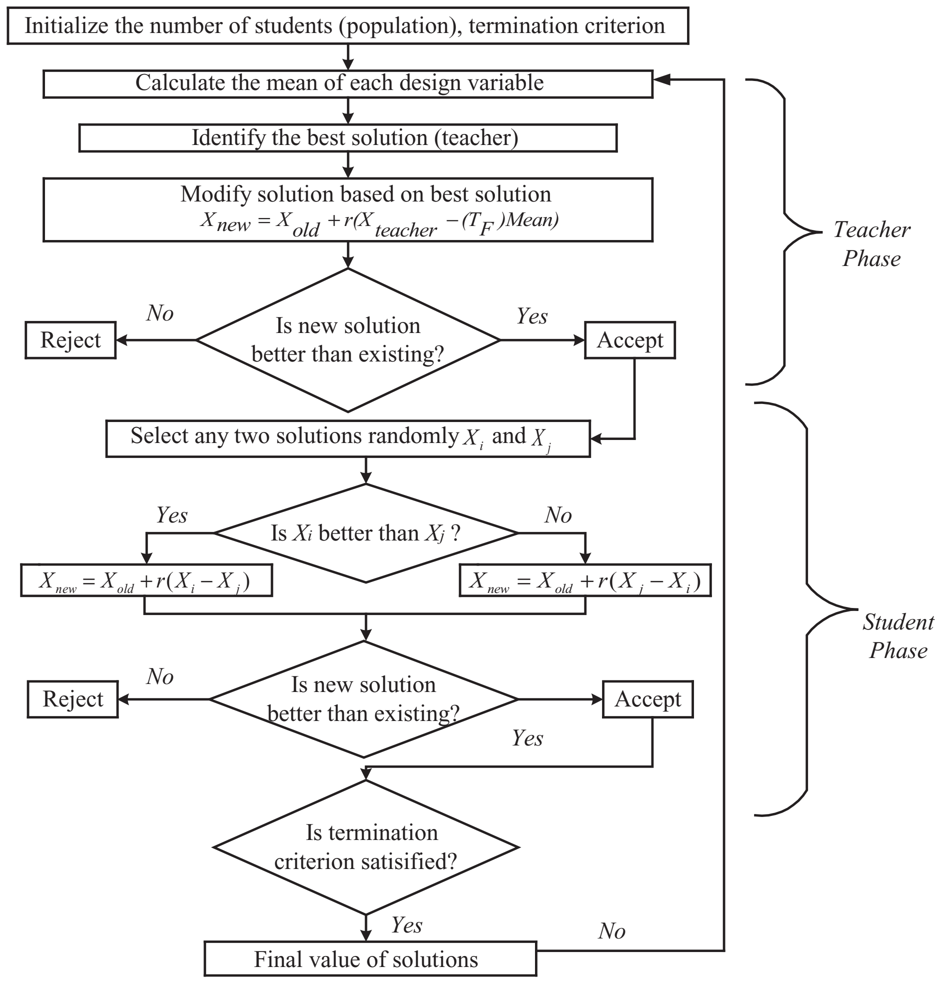

Fig. 2. The flow chart of TLBO algorithm.

published [15,18] conventional and heuristic techniques such as: ZN, GA, FA, hFA-PS based PID controller for the same interconnected power system as shown in Table 2. It can be seen from Table 2 that a smaller ITAE value is obtained with the proposed TLBO optimized PIDD controller (ITAE = 0.6798) compared to TLBO optimized IDD controller (ITAE = 0.7400), hFA-PS (ITAE = 0.7405), FA (ITAE = 0.8023), BFOA (ITAE = 1.5078), GA (ITAE = 2.4668) and ZN (ITAE = 3.4972) based PID controller. Therefore, it can be concluded that the proposed TLBO algorithm outperforms the conventional ZN technique and heuristic techniques FA, BFOA, GA as minimum ITAE value is obtained. Further, it is observed from Table 2 that the performance of proposed TLBO optimized PIDD controller in terms of settling times in frequency and tie-line power deviations is better compared to others.

Table 1
Tuned IDD/PIDD controller parameters.

Controller parameters	IDD	PIDD
Proportional gain (K_P)	–	0.0260
Integral gain (K_I)	0.3215	0.2997
Double derivative gain (K_{DD})	0.1704	0.1819

Table 2
Comparative performance of error and settling time for two area power system.

Techniques/Controller	Settling time (2% band) T_s (s)			ITAE
	ΔF_1	ΔF_2	ΔP_{Tie}	
ZN:PID [15]	15.3	14.1	15.3	3.4972
GA:PID [15]	11.1	11.2	11.0	2.4668
BFOA:PID [15]	9.0	7.9	8.3	1.5078
FA:PID [18]	7.8	6.3	7.9	0.8023
hFA-PS:PID [18]	6.9	5.2	7.5	0.7405
TLBO:IDD	7.3	4.9	6.5	0.7400
Proposed TLBO:PIDD	6.8	3.9	6.5	**0.6798**

Bold signifies the best result.

To study the dynamic performance of the proposed PIDD controller optimized TLBO technique, a step increase in load of 5% is applied at t = 0 s in area-1. The system responses are shown in Fig. 3a–c. For comparison, the simulation results with BFOA, FA, hFA-PS based PID, TLBO tuned IDD and proposed TLBO based PIDD controller for the same power system are also shown in Fig. 3a–c. Critical analysis of the dynamic responses clearly reveals that the proposed PIDD controller performs better than others in terms of settling time, peak over shoot and peak under shoot.

4.3. Sensitivity analysis

Sensitivity analysis is carried out to study the robustness of the system to wide changes in the operating conditions and system parameters [6,10,18,25,26]. Taken one at a time, the operating load condition and time constants of speed governor (T_G) and turbine (T_T) are changed from their nominal values (given in Appendix A) in the range of ±25%. TLBO based PIDD controller is considered due

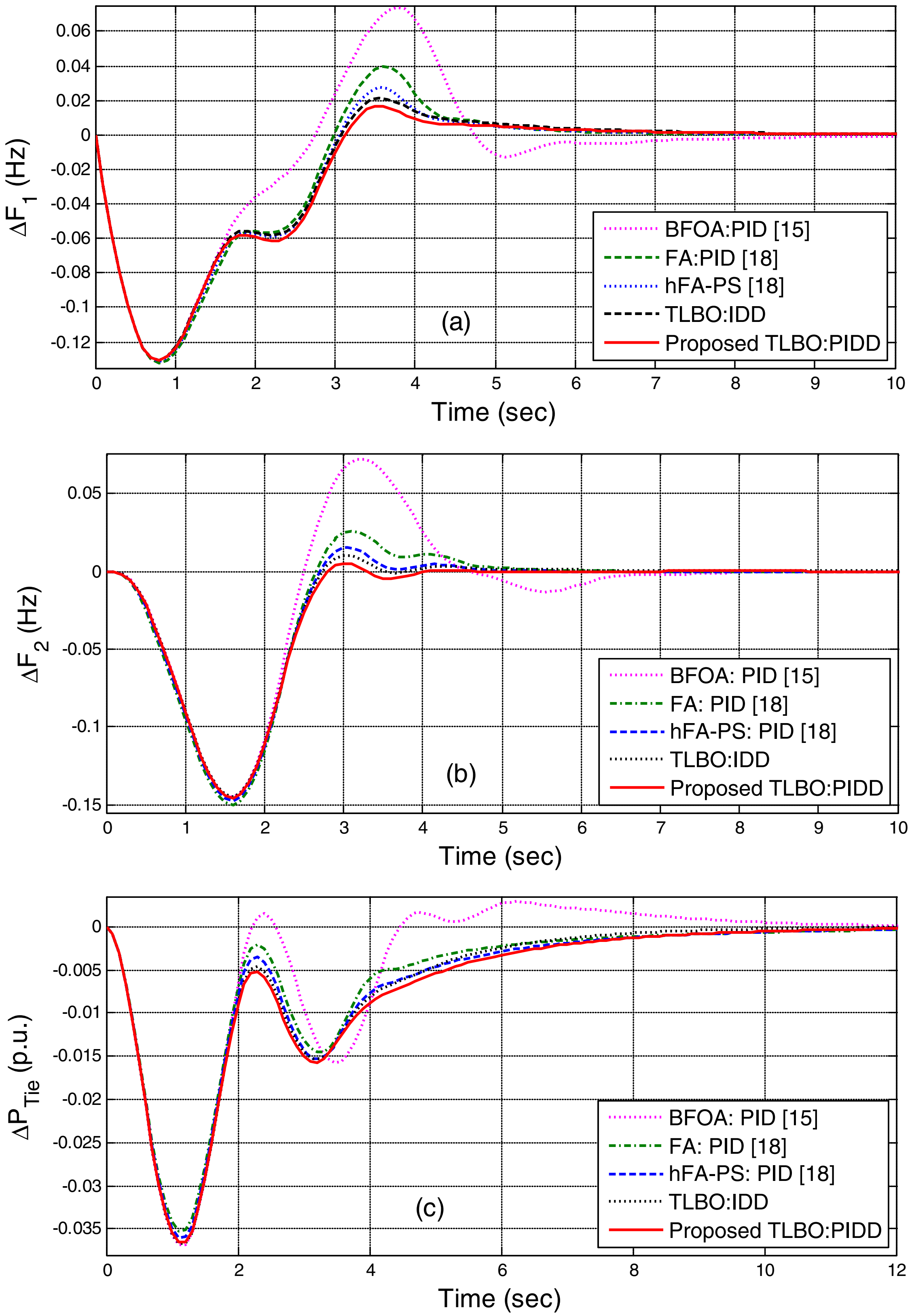

Fig. 3. Dynamic responses of two-area non-reheat thermal power system for 5% step load increase in area-1. (a) Frequency deviation of area-1. (b) Frequency deviation of area-2. (c) Tie-line power deviation.

to its superior performance. The various performance indexes (ITAE values and settling times) under normal and parameter variation cases for the system are shown in Table 3. It can be observed from Table 3 that ITAE and settling time values vary within acceptable ranges. The dynamic performances of the system under variation of parameters are shown in Figs. 4–6. It can be observed from Figs. 4–6 that the effect of the variation of operating loading conditions on the system responses is negligible. So it can be concluded

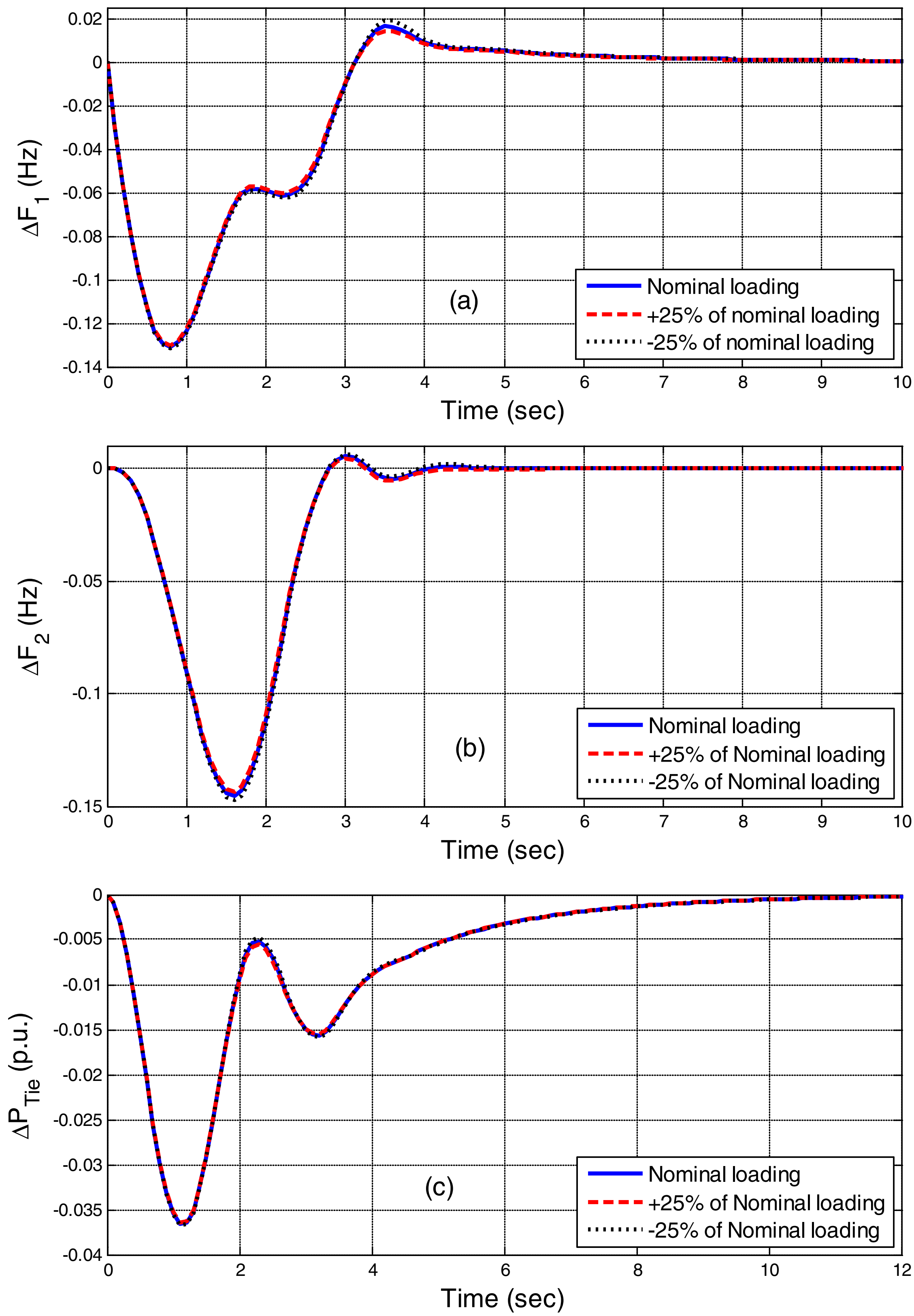

Fig. 4. Dynamic responses of two-area non-reheat thermal power system with variation of loading condition. (a) Frequency deviation of area-1. (b) Frequency deviation of area-2. (c) Tie-line power deviation.

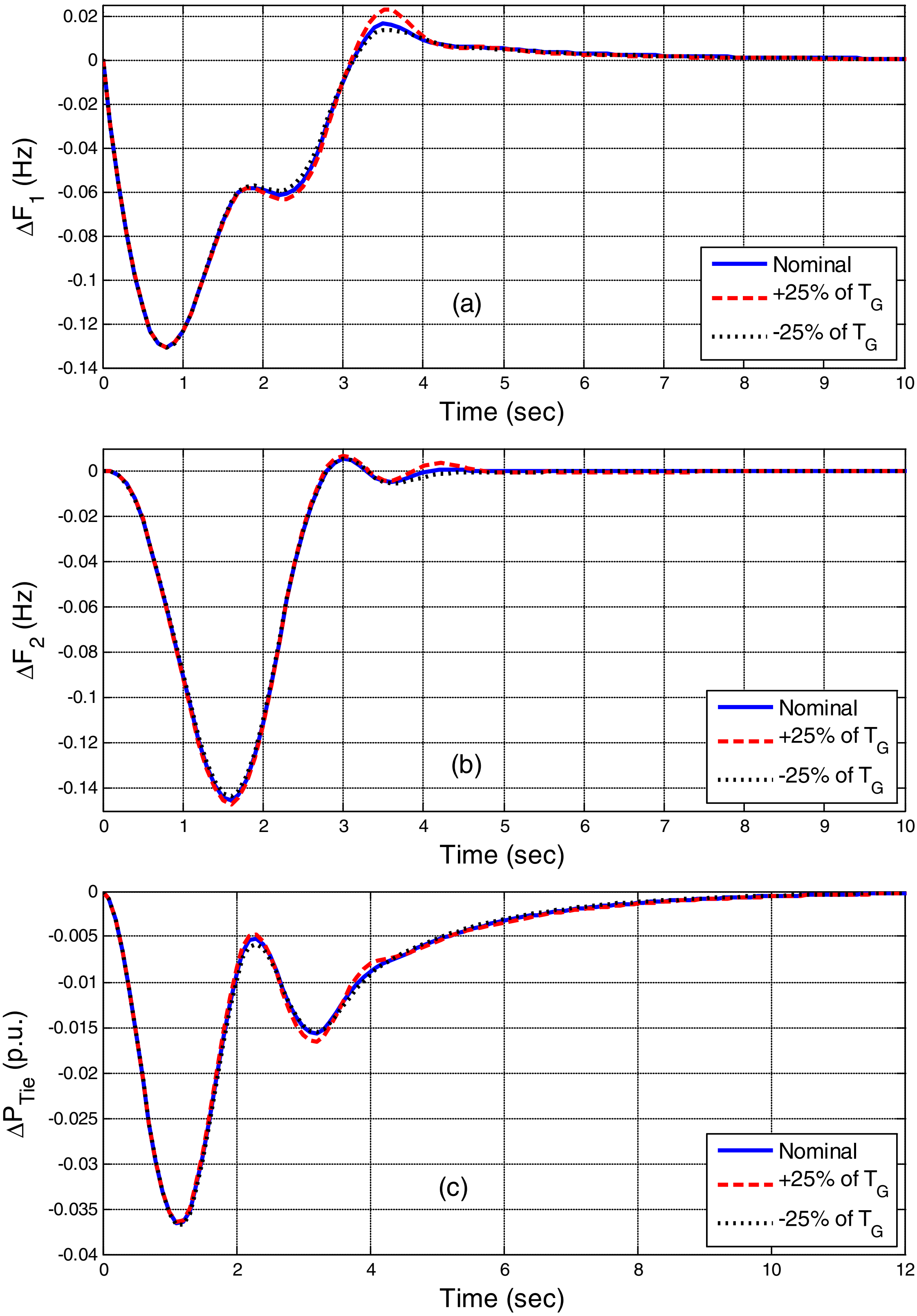

Fig. 5. Dynamic responses of two-area non-reheat thermal power system with variation of T_G. (a) Frequency deviation of area-1. (b) Frequency deviation of area-2. (c) Tie-line power deviation.

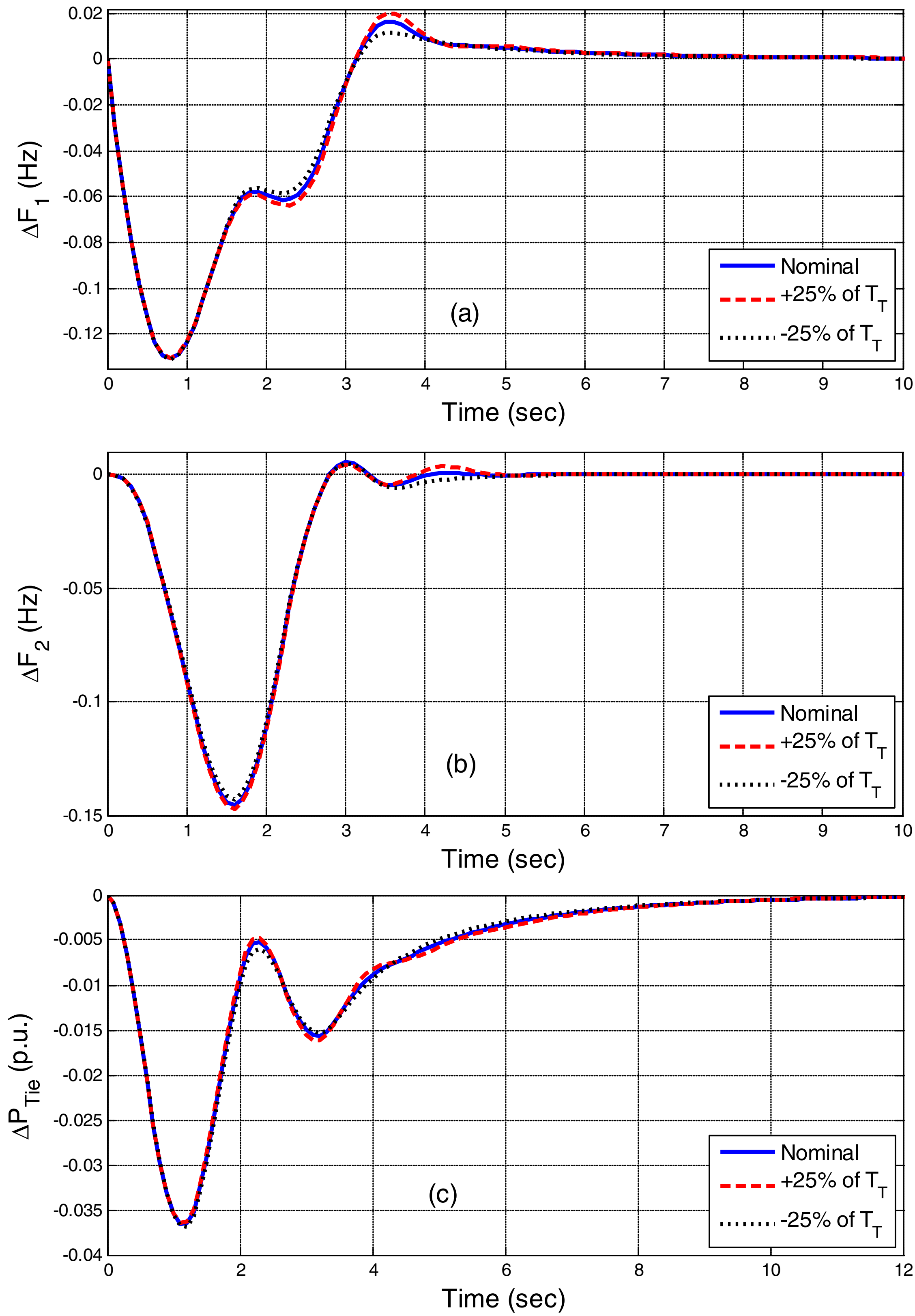

Fig. 6. Dynamic responses of two-area non-reheat thermal power system with variation of T_T. (a) Frequency deviation of area-1. (b) Frequency deviation of area-2. (c) Tie-line power deviation.

Table 3
Sensitivity analysis for two area power system.

Parameter variation	% Change	Settling time T_s (s)			ITAE
		ΔF_1	ΔF_2	ΔP_{Tie}	
Nominal	0	6.8	3.9	6.5	0.6798
Loading condition	+25	6.7	4.0	7.1	0.6932
	−25	7.3	4.0	7.5	0.6878
T_G	+25	6.8	4.7	7.6	0.7291
	−25	6.7	4.2	6.9	0.6865
T_T	+25	7.4	4.8	7.6	0.7035
	−25	6.6	4.4	6.9	0.6909

that the proposed control approach provides a robust and stable control satisfactorily, and the optimum values of controller parameters obtained at the nominal loading with nominal parameters need not be reset for wide changes in the system loading or system parameters.

5. Extension to other power system model

5.1. Multi-area multi-source realistic power system

To demonstrate the ability of proposed TLBO optimized PIDD controller, the study is further extended to a realistic multi-area multi-source interconnected power system as shown in Fig. 7 [17]. Area-1 consists of reheat thermal, hydro and wind power plants. Area-2 consists of reheat thermal, hydro and diesel power plants. To get an accurate insight of the AGC problem, it is essential to include the important inherent requirement and the basic physical constraints and include them in the model. The important constraints which affect the power system performance are boiler dynamics, Generation Rate Constraint (GRC) and Governor Dead Band (GDB). Boiler dynamics configuration is incorporated in thermal plants to generate steam under pressure. Changes in the steam flow and deviations in pressure are sensed and the corresponding action is initiated by the turbine control valves and

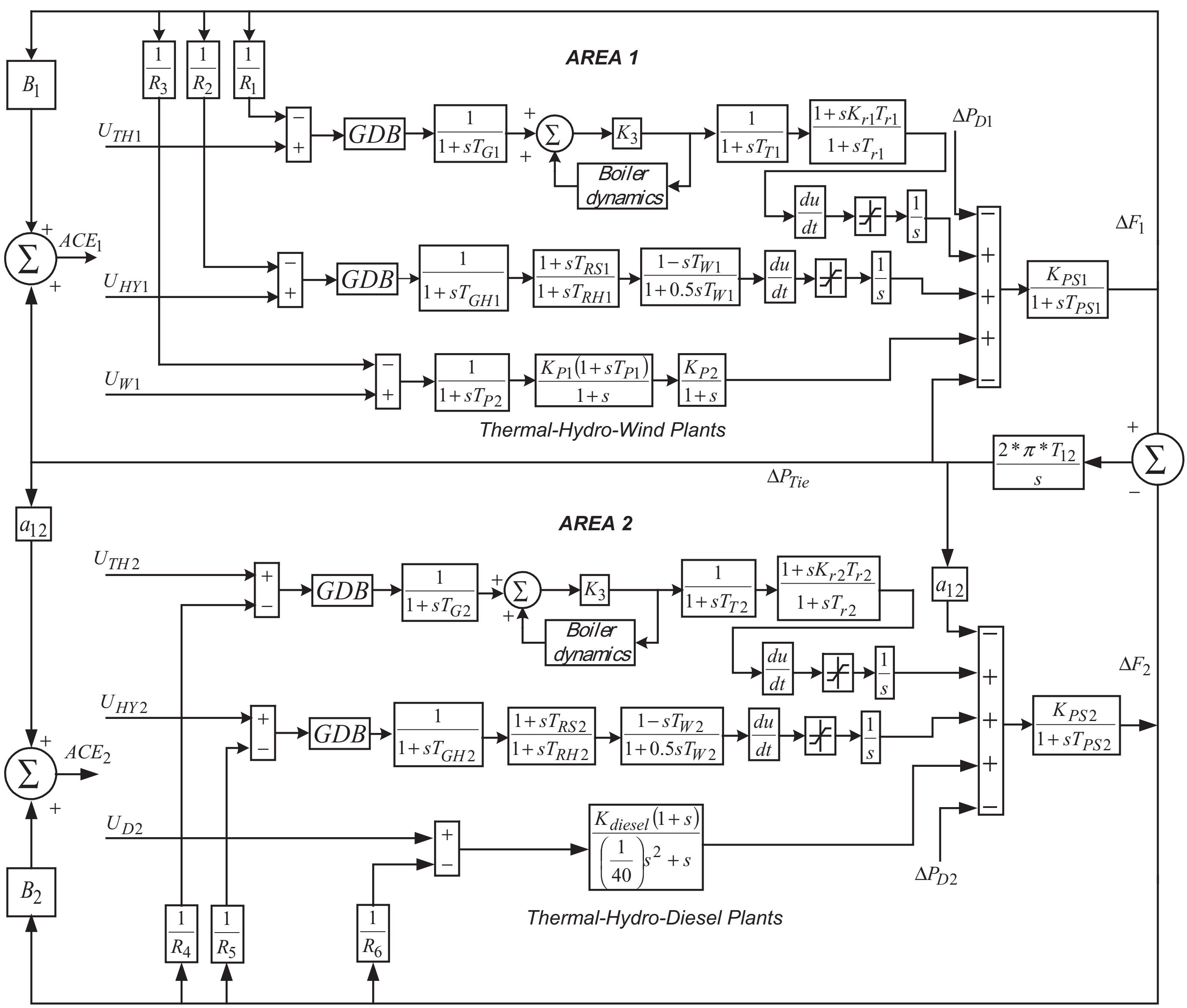

Fig. 7. Transfer function model of multi-area multi-source power system.

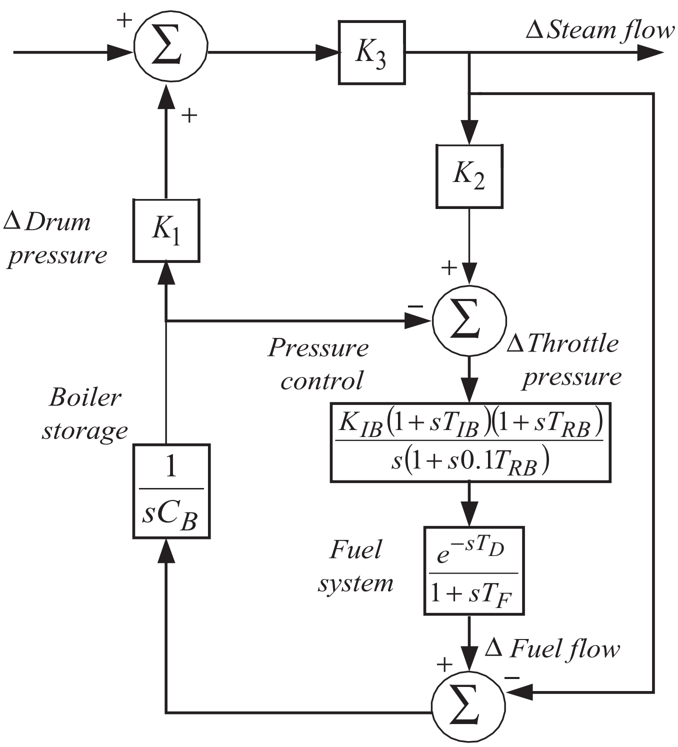

Fig. 8. Block diagram of boiler dynamics configuration.

boiler control. The block diagram of boiler dynamics configuration is shown in Fig. 8. Governor dead band is defined as the total amount of a continued speed change within which there is no change in valve position. Steam turbine dead band is due to the backlash in the linkage connecting the servo piston to the camshaft. Much of this appears to occur in the rack and pinion used to rotate the camshaft that operates the control valves. Due to the governor dead band, an increase/decrease in speed can occur before the position of the valve changes. The speed governor dead band has a great effect on the dynamic performance of electric energy system. The backlash non-linearity tends to produce a continuous sinusoidal oscillation with a natural period of about 2 s. In the present work backlash nonlinearity of 0.05% for the thermal system and 0.02% for hydro system is considered [17]. In a power system, power generation can change only at a specified maximum rate known as Generation Rate Constraint (GRC). In the present study, a GRC of 3% per min is considered for thermal units [17,26]. The GRCs considered for hydro unit are 270% per minute for raising generation and 360% per minute for lowering generation [27]. In view of the above, the effect of boiler dynamics, GRC and GDB are incorporated in the system model as shown in Fig. 7. The nominal parameters of the system under study are given in Appendix B. The participation factors for thermal and hydro are assumed as 0.575 and 0.3 respectively. For wind and diesel same participation factors of 0.125 is assumed.

The same procedure is followed to optimize the controller gains of PID/IDD/PIDD as explained in section 4.1. The optimal values of the controller parameters are given in Table 4. The performance index values are shown in Table 5. From Table 5 it can be seen that minimum ITAE value is obtained with proposed PIDD controller (ITAE = 0.4543) compared to IDD (ITAE = 0.6442), PID (ITAE = 0.9227) optimized TLBO technique and recently published DE optimized PID controller (ITAE = 1.3210) [17]. Further, it is clear from Table 5 that settling times in frequencies and tie-line power deviation are improved with TLBO optimized PIDD controller compared to others. A step increase in load of 1% is applied at t = 0 s in area-1 and the system dynamic performance is shown in Fig. 9a–c. It is evident from Fig. 9a–c that better response is achieved with proposed PIDD controller optimized TLBO technique compared to recently published DE optimized PID controller [17] and PID/IDD optimized TLBO algorithm.

The nominal system parameters of the multi-area multi-source interconnected power system are varied from −25% to +25% to check the robustness of the system. The various performance index values such as ITAE values and settling times under normal and parameter

Table 4
Optimized controller parameters for multi-area multi-source power system.

Controller parameters/Techniques			TLBO		
			PID	IDD	PIDD
Area-1	Thermal	K_P	0.5225	–	0.2883
		K_I	1.9605	0.9221	1.6812
		K_D	1.2691	–	–
		K_{DD}	–	0.0161	0.2442
	Hydro	K_P	0.6127	–	1.2704
		K_I	0.1748	0.2152	0.4265
		K_D	1.9573	–	–
		K_{DD}	–	1.4503	1.5219
	Wind	K_P	1.1955	–	1.6408
		K_I	0.8557	1.5001	1.8705
		K_D	0.4886	–	–
		K_{DD}	–	1.0396	1.1587
Area-2	Thermal	K_P	1.1090	–	1.3393
		K_I	1.8597	1.1202	1.9396
		K_D	1.2793	–	–
		K_{DD}	–	1.5438	1.2423
	Hydro	K_P	0.6524	–	0.9432
		K_I	1.6786	1.2908	0.7505
		K_D	0.5736	–	–
		K_{DD}	–	0.9408	0.9798
	Diesel	K_P	1.1466	–	1.8890
		K_I	1.8503	1.9775	1.9697
		K_D	0.3622	–	–
		K_{DD}	–	0.0254	0.4409

Table 5
Comparative performance of error and settling time for multi-area multi-source power system.

Techniques/Controller	Settling time (2% band) T_s (s)			ITAE
	ΔF_1	ΔF_2	ΔP_{Tie}	
DE:PID [17]	19.68	21.93	25.89	1.3210
TLBO:PID	18.22	18.88	16.28	0.9227
TLBO:IDD	17.95	18.72	13.01	0.6442
TLBO:PIDD	16.14	16.79	12.77	0.4543

Table 6
Robustness analysis for multi-area multi-source power system.

Parameter variation	% Change	Settling time (2% band) T_s(s)			ITAE
		ΔF_1	ΔF_2	ΔP_{Tie}	
Nominal	**0**	**16.14**	**16.79**	**12.77**	**0.4543**
Loading condition	+25	16.14	16.79	12.78	0.4542
	−25	16.14	16.78	12.76	0.4544
T_G	+25	16.12	16.77	12.75	0.4543
	−25	16.16	16.81	12.79	0.4543
T_T	+25	16.06	16.70	12.70	0.4542
	−25	16.21	16.87	12.83	0.4544
T_{GH}	+25	16.06	16.71	12.74	0.4574
	−25	16.25	16.89	12.81	0.4418
T_{RH}	+25	16.13	16.78	12.76	0.4621
	−25	16.12	16.77	12.77	0.4464
R	+25	16.05	16.73	12.77	0.4577
	−25	16.35	16.93	12.80	0.4500

Bold signifies the best result.

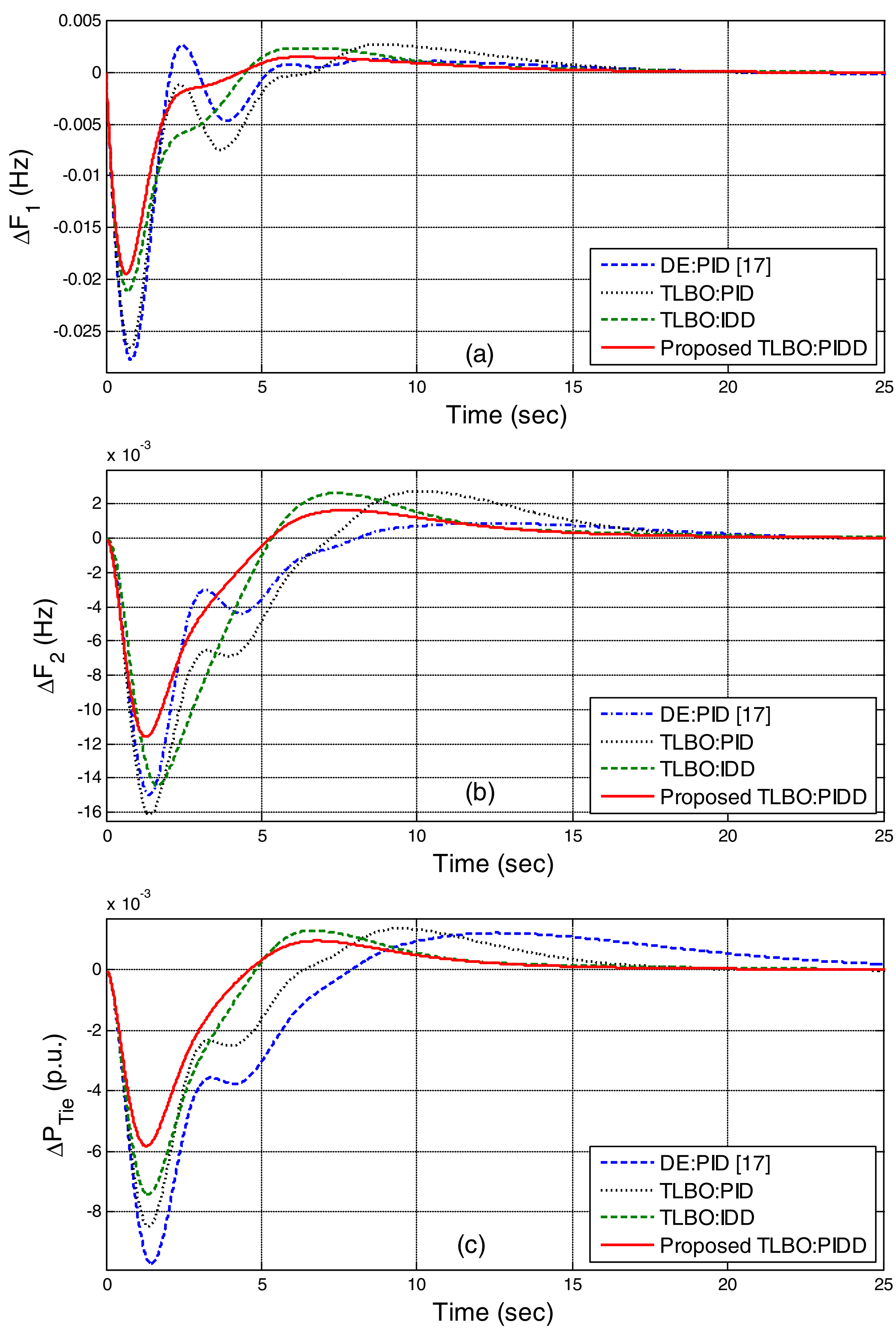

Fig. 9. Dynamic responses of multi-area multi-source power system for 1% step load increase in area-1. (a) Frequency deviation of area-1. (b) Frequency deviation of area-2. (c) Tie-line power deviation.

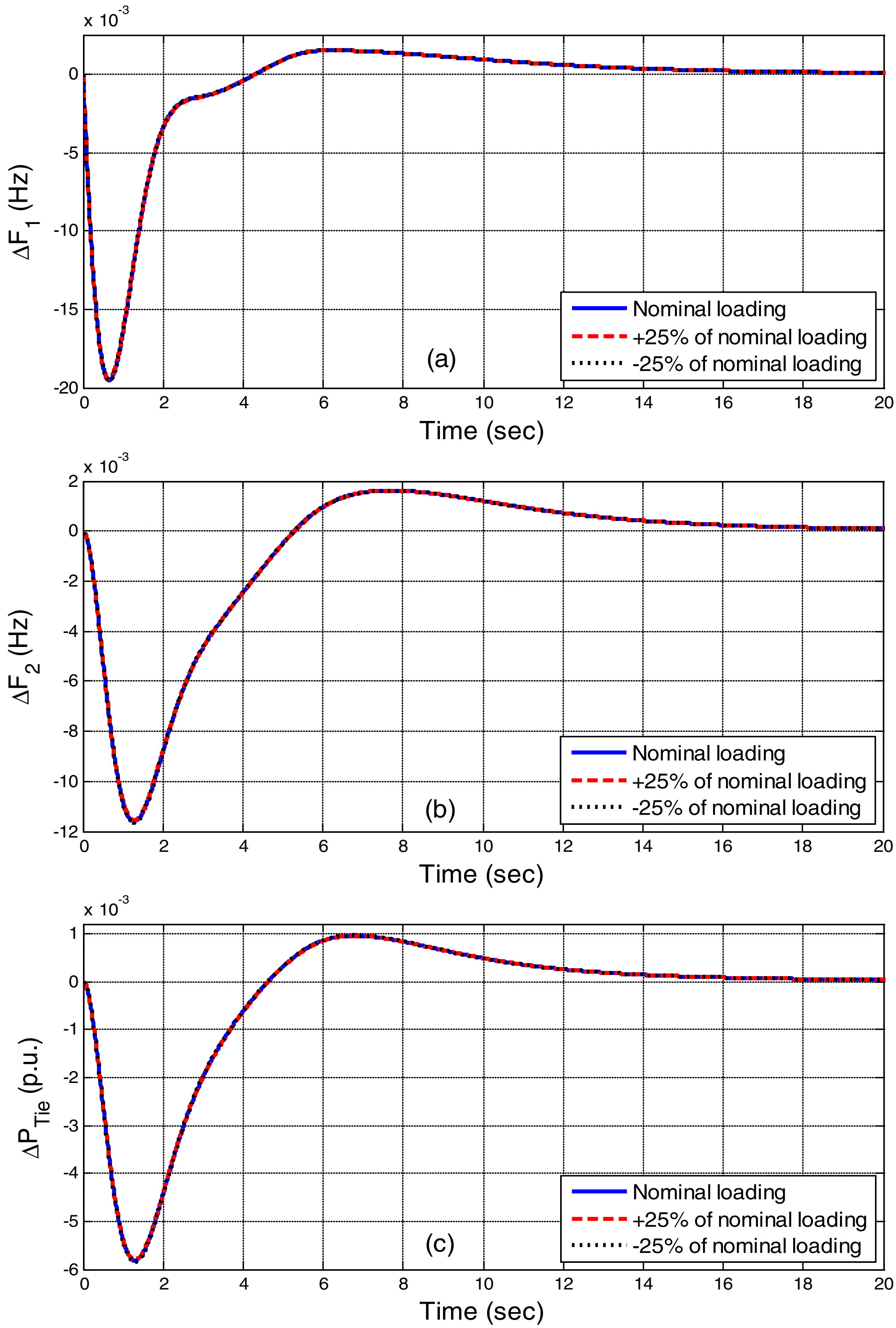

Fig. 10. Dynamic responses of multi-area multi-source power system with variation of loading condition. (a) Frequency deviation of area-1. (b) Frequency deviation of area-2. (c) Tie-line power deviation.

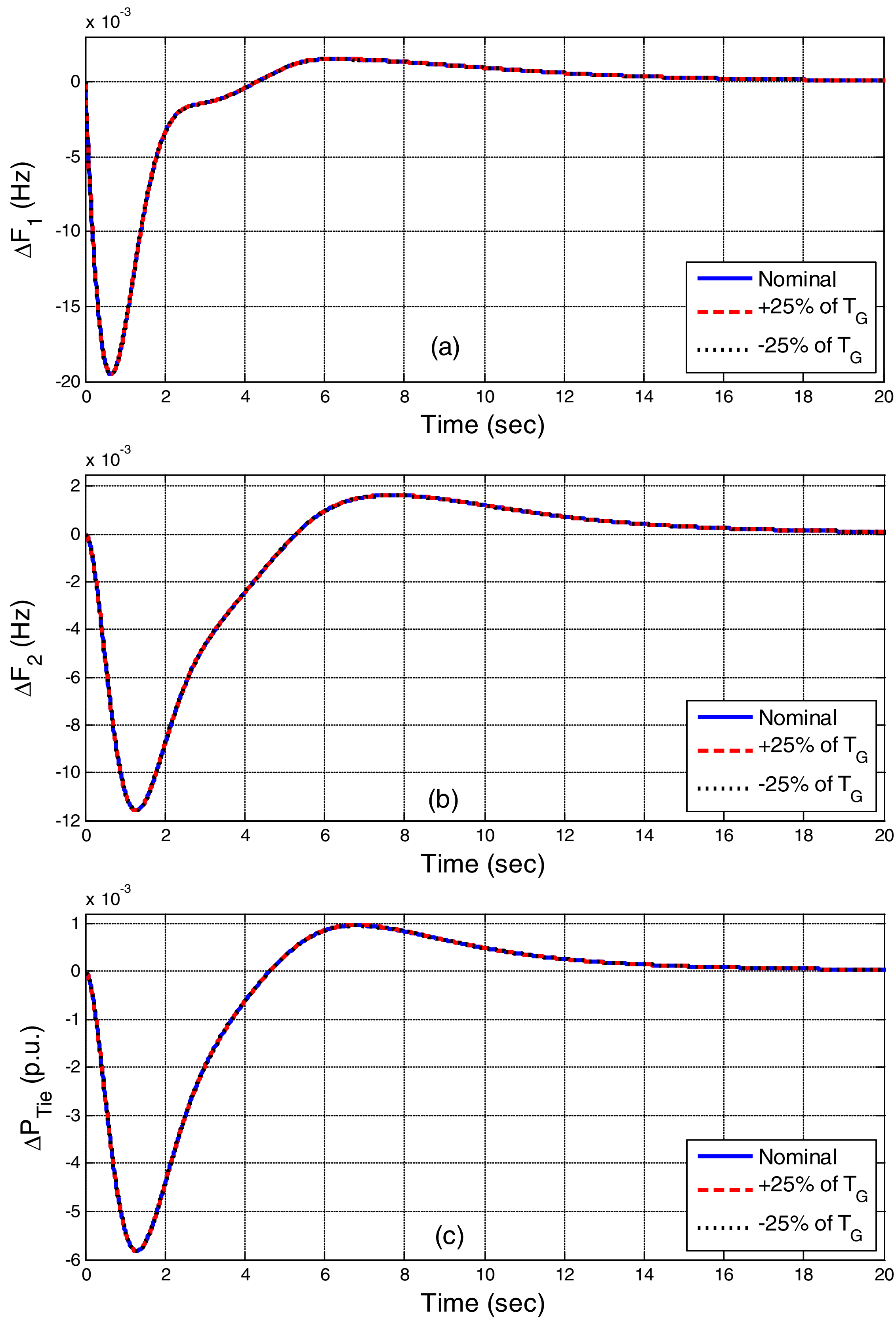

Fig. 11. Dynamic responses of multi-area multi-source power system with variation of T_G. (a) Frequency deviation of area-1. (b) Frequency deviation of area-2. (c) Tie-line power deviation.

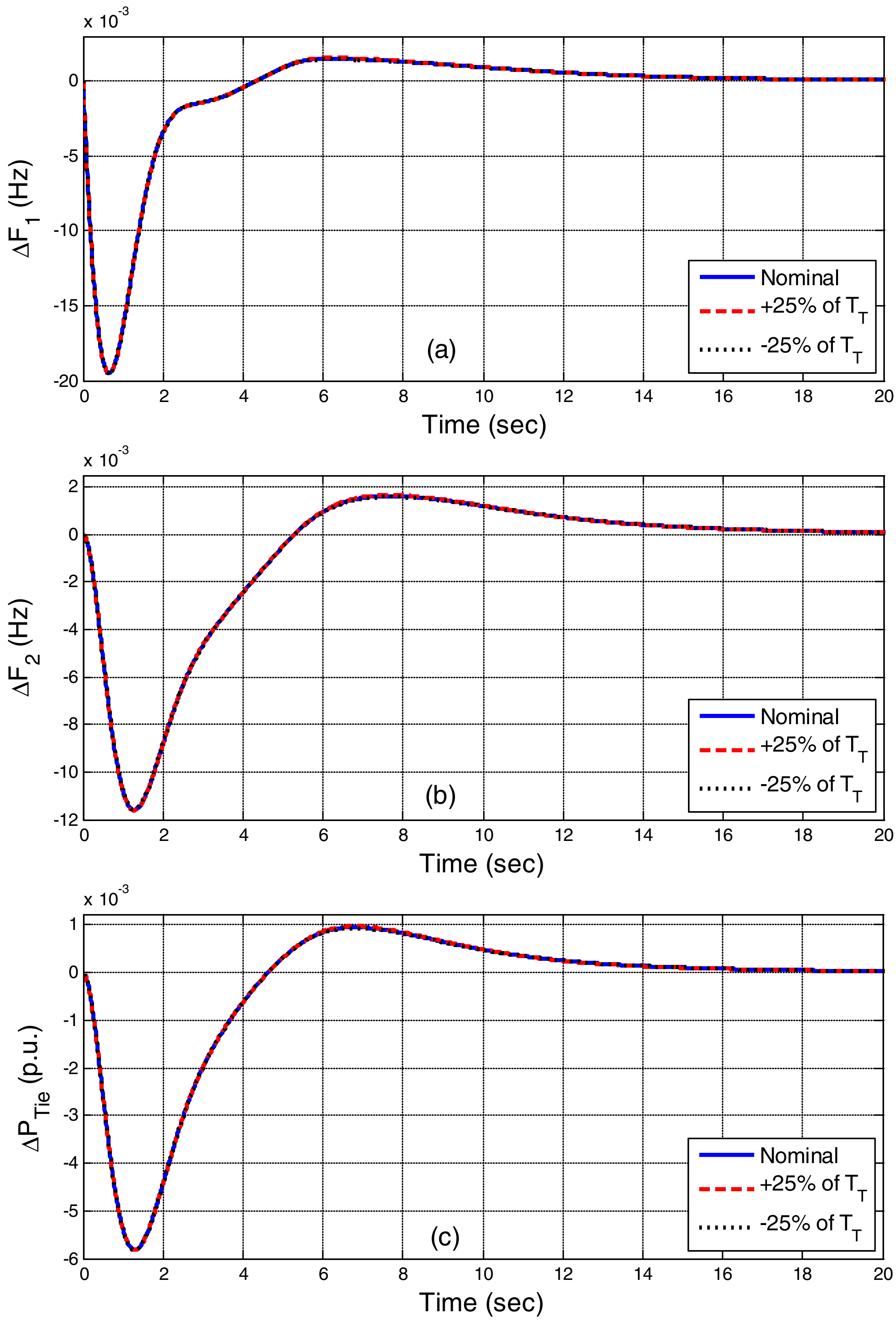

Fig. 12. Dynamic responses of multi-area multi-source power system with variation of T_T. (a) Frequency deviation of area-1. (b) Frequency deviation of area-2. (c) Tie-line power deviation.

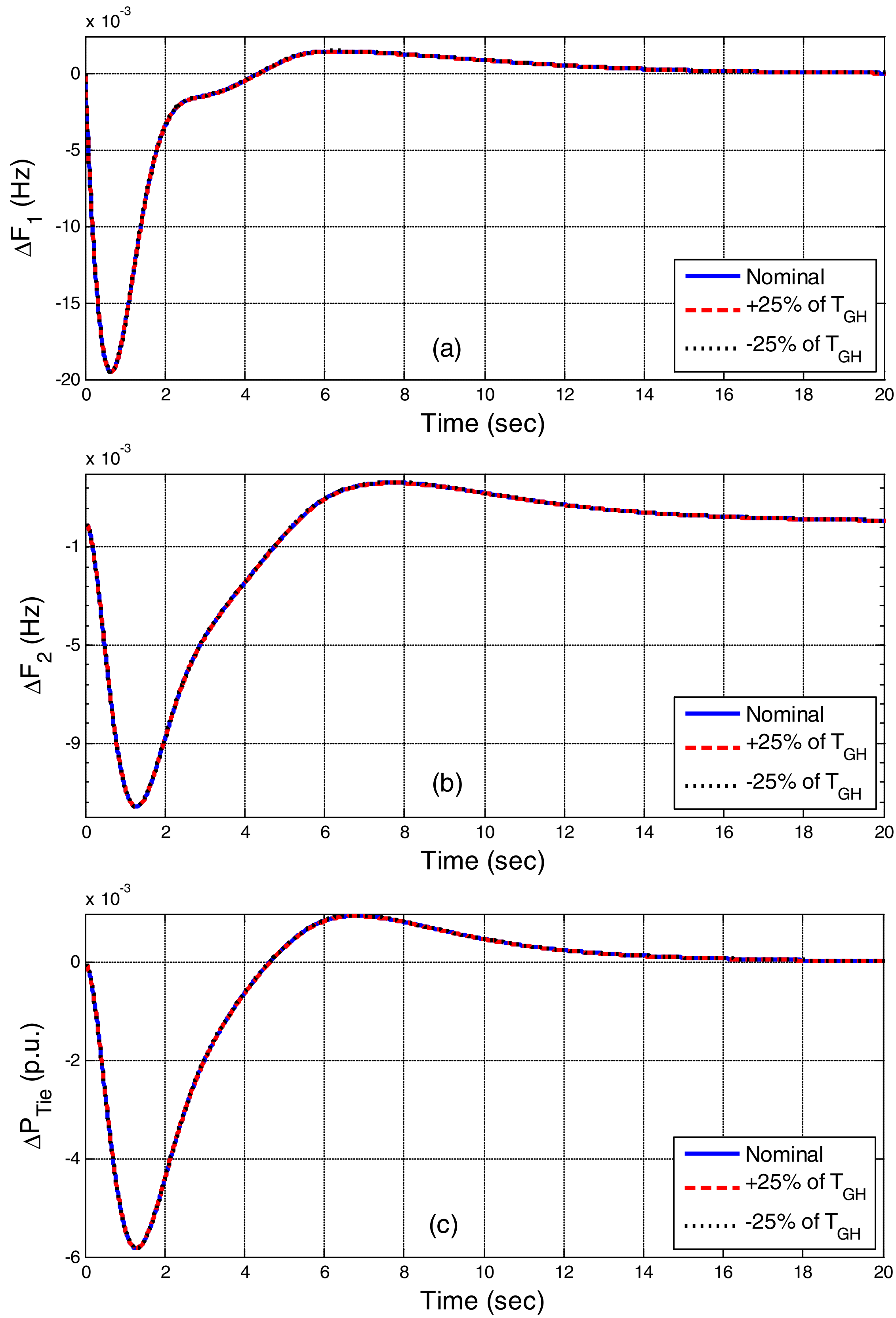

Fig. 13. Dynamic responses of multi-area multi-source power system with variation of T_{GH}. (a) Frequency deviation of area-1. (b) Frequency deviation of area-2. (c) Tie-line power deviation.

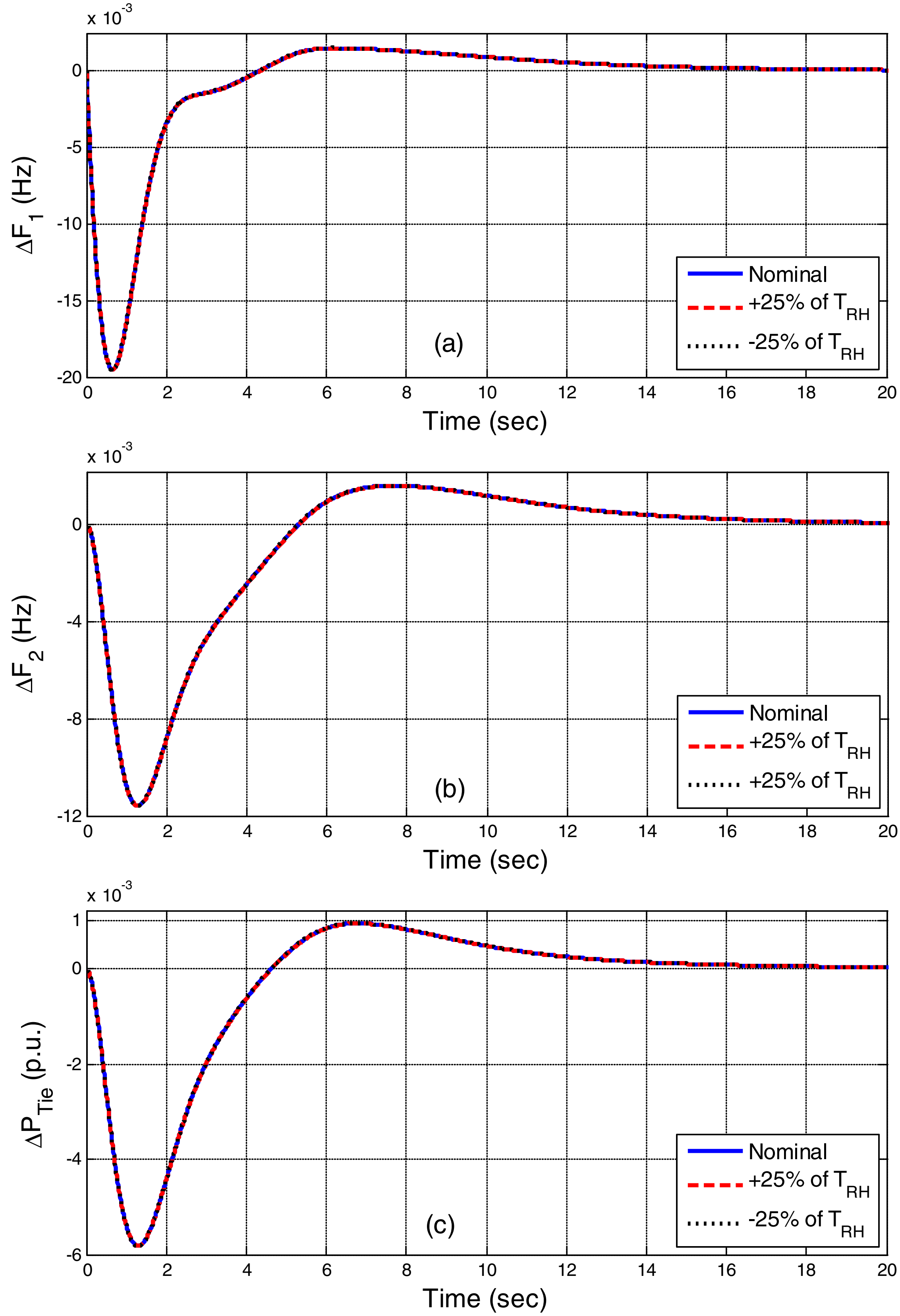

Fig. 14. Dynamic responses of multi-area multi-source power system with variation of T_{RH}. (a) Frequency deviation of area-1. (b) Frequency deviation of area-2. (c) Tie-line power deviation.

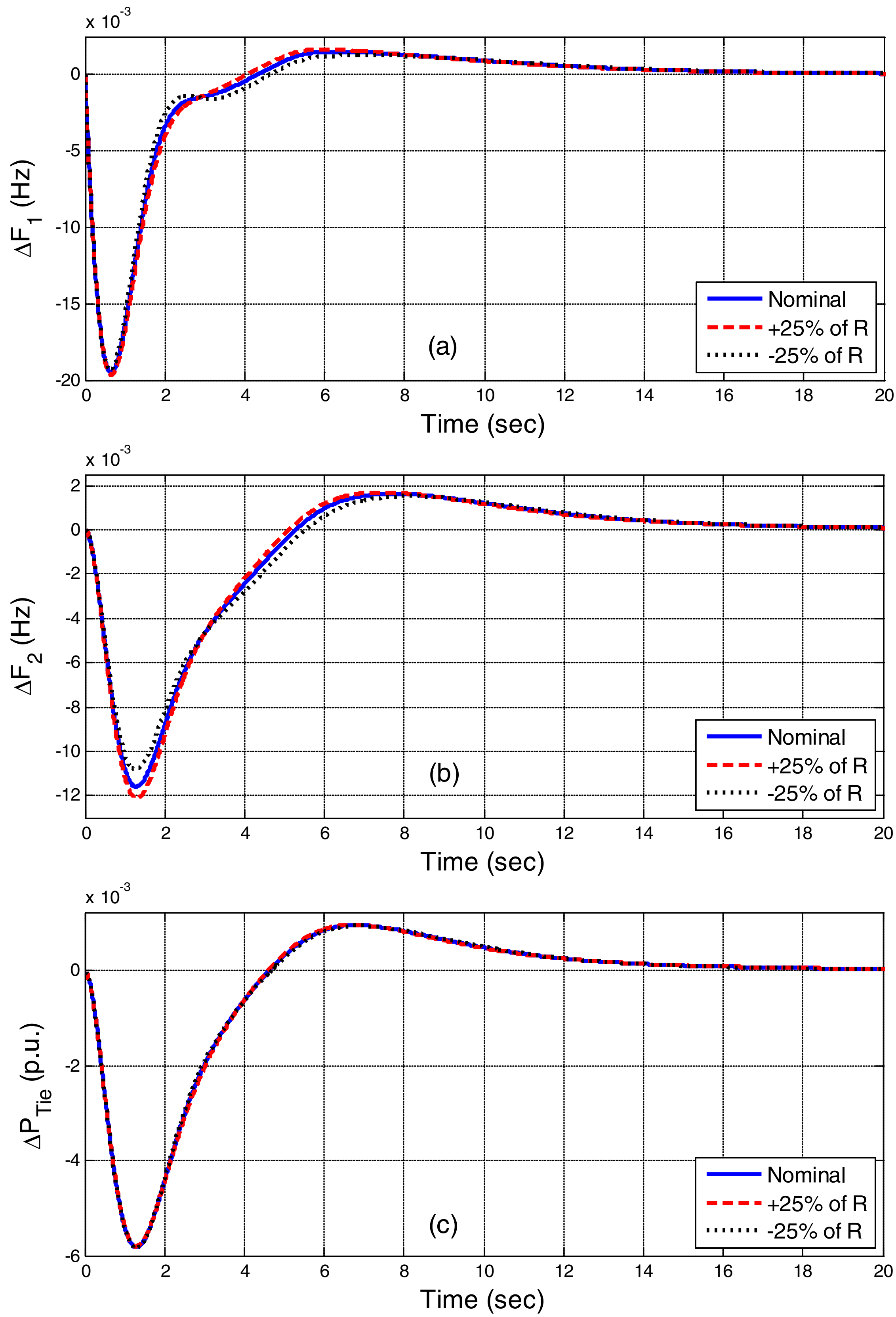

Fig. 15. Dynamic responses of multi-area multi-source power system with variation of R. (a) Frequency deviation of area-1. (b) Frequency deviation of area-2. (c) Tie-line power deviation.

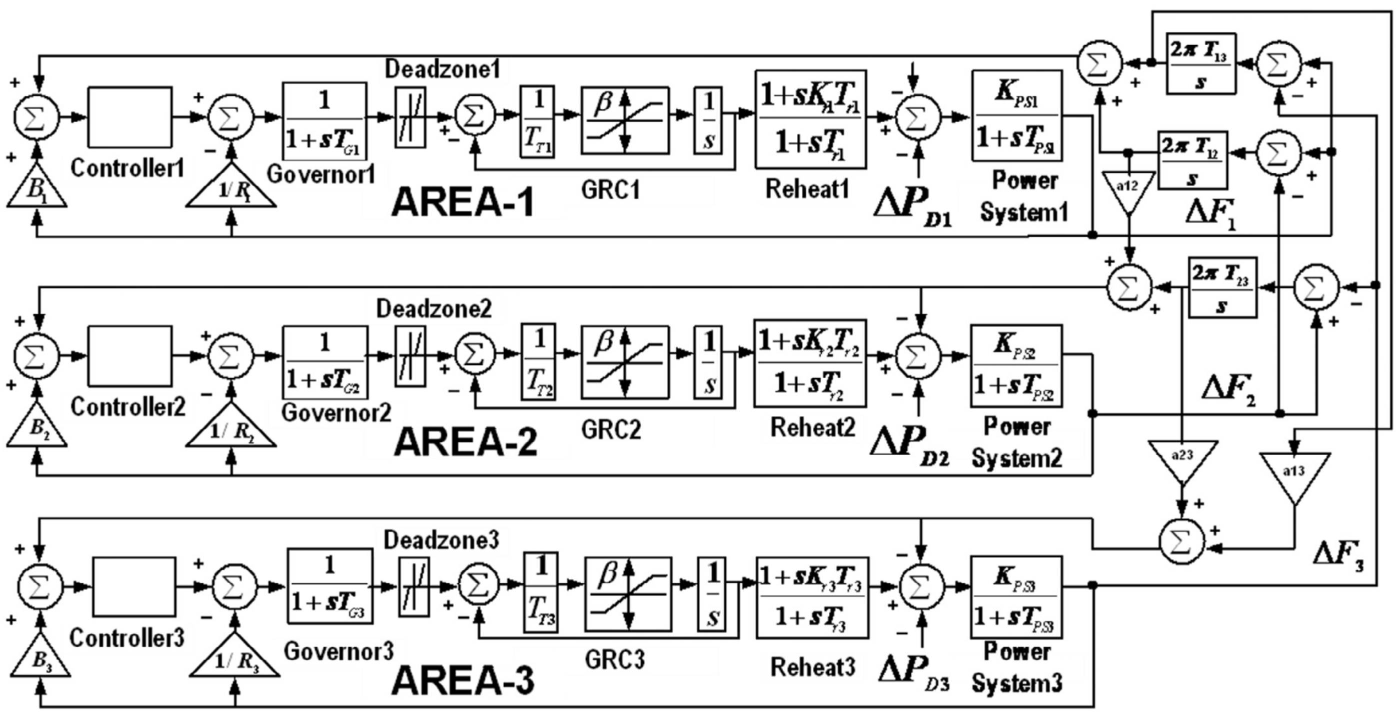

Fig. 16. Transfer function model of the three-area unequal thermal power system with reheat, GRC and GDB.

variations are given in Table 6. Critical examination of Table 6 clearly reveals that the performance indexes vary within acceptable ranges and are close to their respective values obtained with nominal system parameters. The dynamic performance of the system with the varied conditions of loading, T_G, T_T, T_{GH}, T_{RH} and R are shown in Figs. 10–15. It can be observed from Figs. 10–15 that the effect of the variation of operating loading conditions and system time constants on the system responses is negligible. Hence it can be concluded that the proposed control approach provides a robust, stable control satisfactorily.

5.2. Three unequal area thermal power system with GRC and GDB non-linearity

In order to demonstrate the potential and effectiveness of the proposed approach, it is further applied to a three-unequal area thermal power system [21] considering appropriate generation rate constraint and governor dead band nonlinearity as shown in Fig. 16. The system consists of three-unequal area interconnected power systems (Area-1: 2000 MW, Area-2: 4000 MW, and Area-3: 8000 MW). The relevant parameters are given in Appendix C. To tune the proposed PIDD controller parameters, the same procedure as presented in section 4.1 is followed. The final controller parameters obtained for each area using proposed TLBO algorithm employing ITAE objective function are:

Area-1: $K_{P1} = -0.5992$, $K_{I1} = -0.5107$, $K_{DD1} = -0.3464$
Area-2: $K_{P2} = -0.2241$, $K_{I2} = -0.1943$, $K_{DD2} = -0.6651$
Area-3: $K_{P1} = -0.0816$, $K_{I1} = -0.8385$, $K_{DD1} = -0.2151$

The performance index such as settling times (2% of final value) and ITAE values with proposed TLBO optimized PIDD controller are given in Table 7. To show the superiority of the proposed approach, the best claimed results of FA [21] optimized PID controller for the same interconnected power system are also provided in Table 7. From Table 7 it is clear that the proposed TLBO optimized PIDD controller, the ITAE value (ITAE = 20.4041) is reduced by 33.97% compared to published FA [21] optimized PID controller (ITAE = 20.4041) for the same interconnected power system. Settling times of ΔF_1, ΔF_2, ΔF_3, $\Delta P_{Tie,12}$, $\Delta P_{Tie,13}$ and $\Delta P_{Tie,23}$ with proposed TLBO tuned PIDD controller are 27.41%, 32.41%, 31%, 2.6%, 0.2% and 23.48% respectively improved compared to FA optimized PID controller. The comparative dynamic responses of the system are shown in Fig. 17a–f for 10% step load disturbance is applied in area-1 at t = 0 s. It can be easily seen from Fig. 17a–f that the system response is much better in terms of settling time and the overshoots with proposed approach compared to recently published FA optimized PID controller. The performance of the proposed approach is further investigated for a different operating condition with variation of system parameters and loading conditions by ±25% from their nominal values to test the robustness. Table 8 shows the performance indexes (ITAE values and settling times) with the varied system conditions. It can be observed from Table 8 that the performance indexes are more or less the same and the effect of the variation in operating loading conditions and system time constants on the system performance

Table 7
Comparative performance of error and settling time for three-unequal thermal power system.

Techniques/Controller	Settling time (2% band) T_s (s)						ITAE
	ΔF_1	ΔF_2	ΔF_3	$\Delta P_{Tie,12}$	$\Delta P_{Tie,13}$	$\Delta P_{Tie,23}$	
FA:PID [21]	26.56	26.72	26.55	24.03	19.66	20.70	30.9001
TLBO:PIDD	19.28	18.06	18.31	23.39	19.23	15.84	20.4041

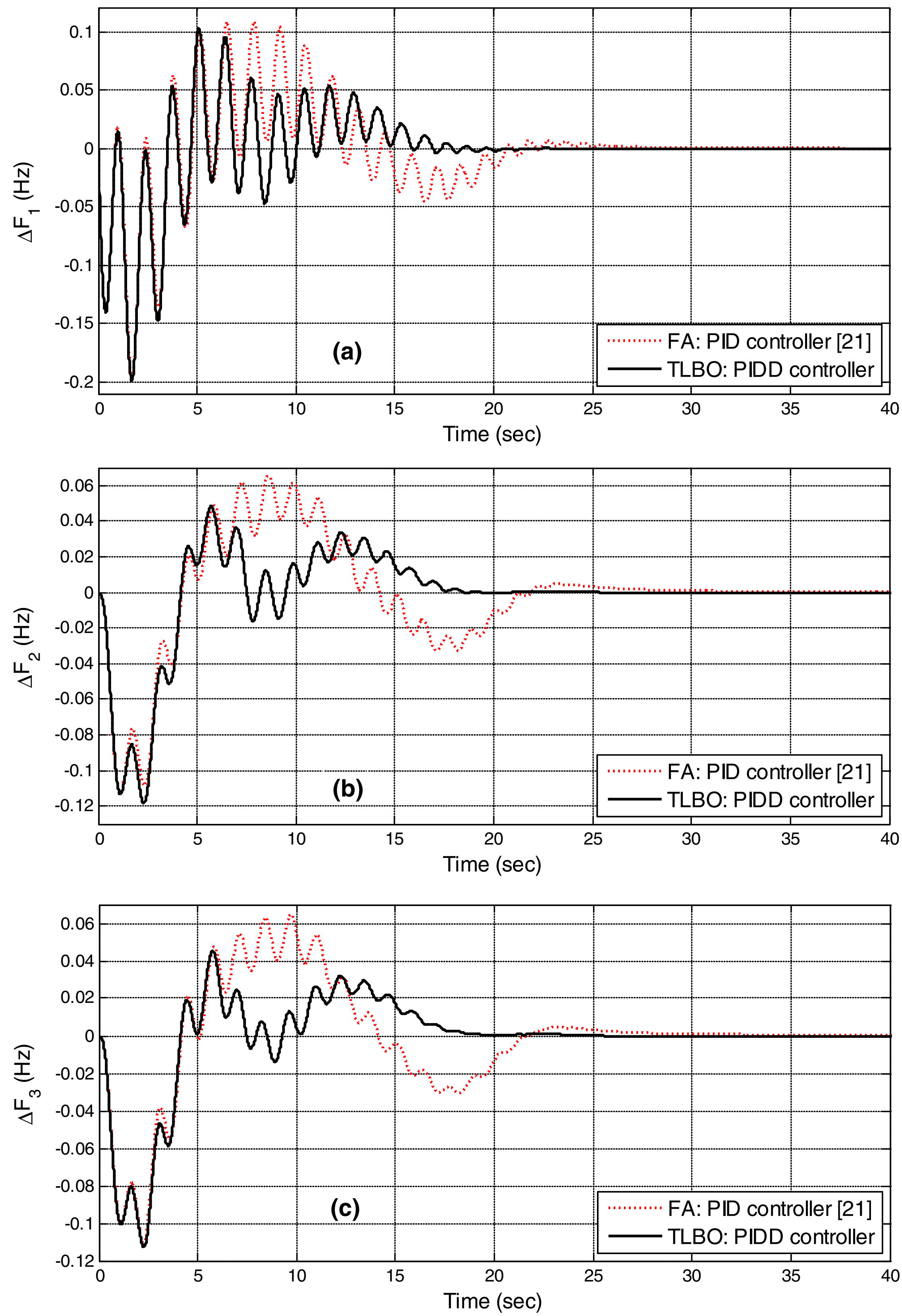

Fig. 17. Dynamic responses of the system for 10% step load increase in area-1. (a) Frequency deviation of area-1. (b) Frequency deviation of area-2. (c) Frequency deviation of area-3. (d) Tie-line power deviation between area 1 and 2. (e) Tie-line power deviation between area 1 and 3. (f) Tie-line power deviation between area 2 and 3.

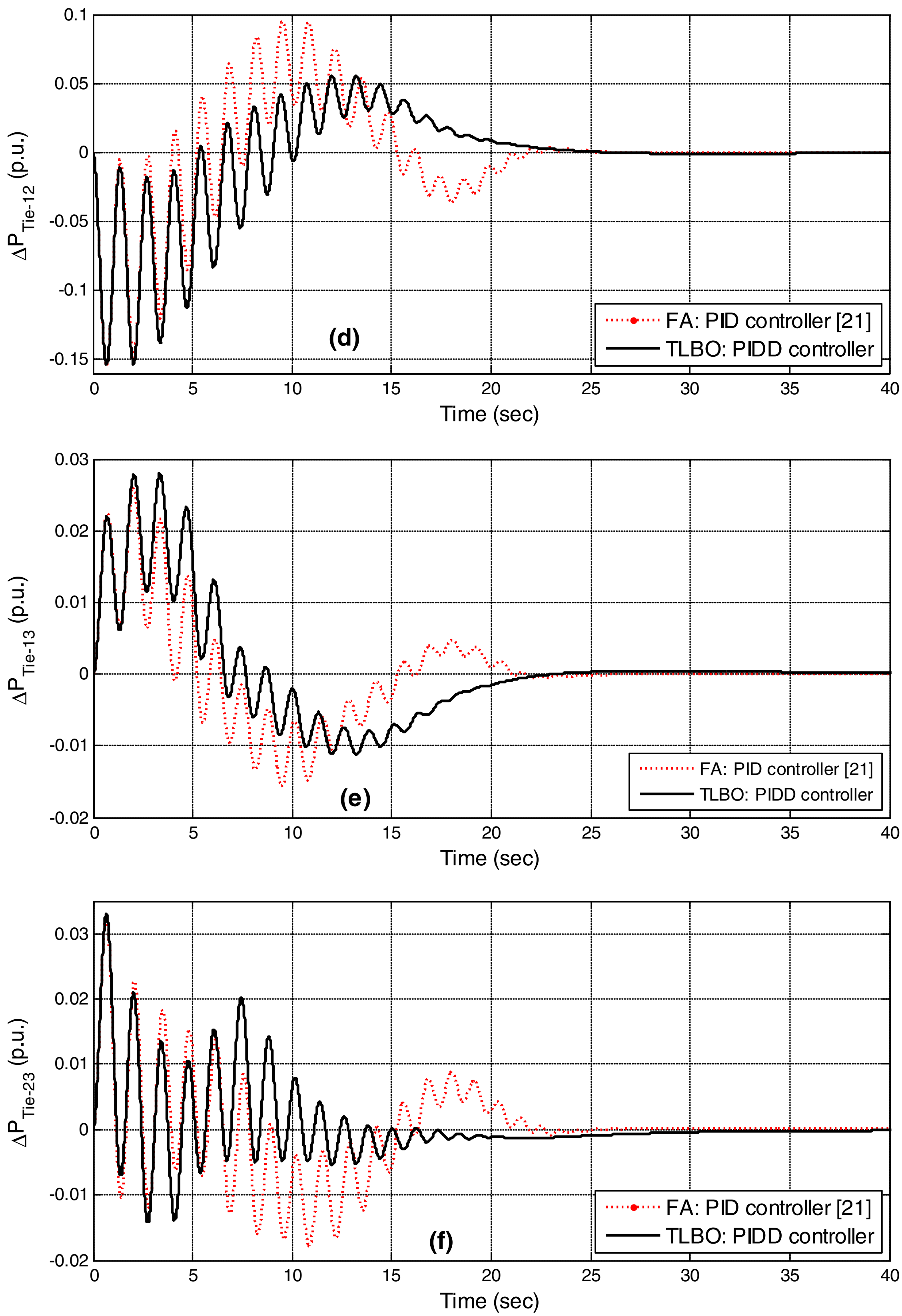

Fig. 17. (*continued*)

Table 8
Sensitivity analysis under varied conditions for three-unequal thermal power system.

Parameter variation	% Change	Settling time T_s (s)						ITAE
		ΔF_1	ΔF_2	ΔF_3	$\Delta P_{Tie,12}$	$\Delta P_{Tie,13}$	$\Delta P_{Tie,23}$	
Nominal	0	19.28	18.06	18.31	23.39	19.23	15.84	20.4041
Loading condition	+25	18.46	17.91	19.19	23.60	18.91	14.54	18.4688
	–25	21.66	20.99	18.68	23.29	19.60	18.27	23.2985
T_G	+25	23.81	22.34	21.38	22.63	19.69	19.47	23.5468
	–25	18.35	19.84	19.87	24.01	19.12	14.44	18.8464
T_T	+25	21.71	20.15	18.59	22.65	19.44	18.21	21.5080
	–25	17.56	17.24	18.20	23.88	19.12	15.59	19.7571
R	+25	20.36	19.78	17.41	23.19	19.24	15.69	20.7292
	–25	19.72	19.29	19.46	23.89	19.21	19.01	20.8883

is negligible. As an example, the frequency deviation response of area-1 with the varied loading condition is shown in Fig. 18. It can be observed from Fig. 18 that the effect of the variation of loading condition on the system performance is negligible. Therefore it can be concluded that the proposed control strategy provides a robust control under wide changes in the system loading or system parameters.

6. Conclusion

In this paper, an attempt has been made to apply a Teaching Learning Based Optimization (TLBO) algorithm based on PIDD controllers for Automatic Generation Control (AGC) of multi-area multi-source interconnected power system. Firstly, a two-area power system with GRC is considered. The superiority of the proposed design approach has been shown by comparing the results with some recently published modern heuristic optimization techniques such as hFA-PS, FA, BFOA, GA and ZN for the same interconnected power system. Then further, the analysis is extended to more realistic diverse source power system including the nonlinearities. It is observed from simulation result that TLBO optimized PIDD controller performed better compared to recently published DE optimized PID controller and also TLBO optimized PID and IDD controllers. The system performance indexes such as ITAE and settling times reveal that the proposed approach proves its effectiveness more than others. The proposed approach is also extended to a three unequal area thermal power system considering nonlinearity effects of GRC and governor dead band (GDB). The simulation results show that the performance of the system has been improved in terms of settling time and overshoot with proposed TLBO optimized PIDD controller compared to FA optimized PID controller. Finally, the robustness analysis is carried out to test the robustness of the proposed PIDD controller for the above three test systems. Investigations clearly reveal that the proposed TLBO optimized PIDD controller parameters need not be reset even if the system is subjected to wide variation in loading condition and system parameters.

Appendix A

Two-area thermal power system [8,15,22]
$F = 60$ Hz, $B_1 = B_2 = 0.425$ p.u. MW/Hz; $R_1 = R_2 = 2.4$ Hz/p.u.; $T_{G1} = T_{G2} = 0.08$ s; $T_{T1} = T_{T2} = 0.3$ s; $K_{P1} = K_{P2} = 120$ Hz/p.u.; $T_{P1} = T_{P2} = 20$ s; $T_{12} = 0.545$ p.u.; $a_{12} = -1$.

Appendix B

Multi-area multi-source power system [17]
$F = 60$ Hz; $B_1 = B_2 = 0.425$ p.u. MW/Hz; $T_{G1} = T_{G2} = 0.08$ s; $T_{T1} = T_{T2} = 0.3$ s; $K_{r1} = K_{r2} = 0.333$; $T_{r1} = T_{r2} = 10$ s; $T_{GH1} = T_{GH2} = 48.7$ s; $T_{RS1} = T_{RS2} = 0.513$ s; $T_{RH1} = T_{RH2} = 10$ s; $T_{W1} = 1$; $K_{diesel} = 16.5$; $K_{P1} = 1.25$; $K_{P2} = 1.4$; $T_{P1} = 6$; $T_{P2} = 0.041$; $R_1 = R_2 = R_3 = R_4 = R_5 = R_6 = 2.4$ Hz/p.u.; $K_1 = 0.85$; $K_2 = 0.095$; $K_3 = 0.92$; $K_{IB} = 0.03$; $T_{IB} = 26$; $T_{RB} = 6.9$; $C_B = 200$; $T_D = 0$; $T_F = 10$; $K_{PS1} = K_{PS2} = 120$ Hz/p.u. MW; $T_{PS1} = T_{PS2} = 20$ s; $T_{12} = 0.0866$ p.u.; $a_{12} = -1$.

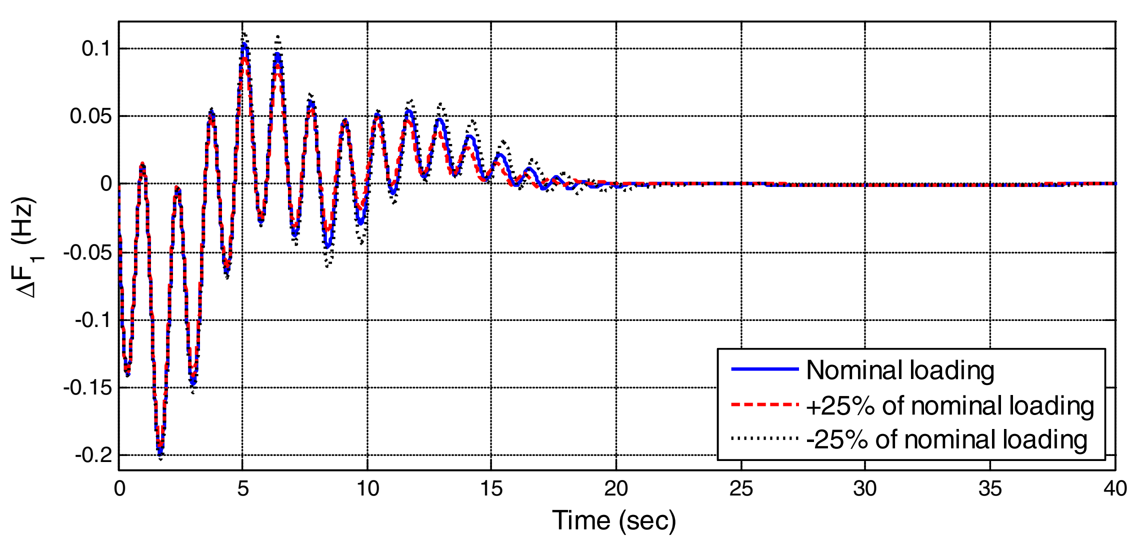

Fig. 18. Dynamic responses of the system with variation of loading condition for the three unequal thermal system.

Appendix C

Three-unequal area thermal power system [21]

$f = 60\,(\mathrm{Hz})$; $B_1 = 0.3483$, $B_2 = 0.3827$, $B_3 = 0.3692\,(\mathrm{p.u.\,Hz})$; $D_1 = D_3 = 0.015$, $D_2 = 0.016\,(\mathrm{p.u.\,Hz})$; $2H_1 = 0.1667$, $2H_2 = 0.2017$, $2H_3 = 0.1247$, $(\mathrm{p.u.}\ \ \mathrm{s})$; $R_1 = 3.0$, $R_2 = 2.73$, $R_3 = 2.82\,(\mathrm{Hz/p.u.})$; $T_{g1} = 0.08$, $T_{g2} = 0.06$, $T_{g3} = 0.07\,(\mathrm{s})$; $T_{t1} = 0.4$, $T_{t2} = 0.44$, $T_{t3} = 0.3\,(\mathrm{s})$; $K_{r1} = K_{r2} = K_{r3} = 0.5$; $T_{r1} = T_{r2} = T_{r3} = 10\,(\mathrm{s})$, $T_{12} = 0.2$, $T_{23} = 0.12$, $T_{31} = 0.25\,(\mathrm{p.u./Hz})$, $P_{R1} = 2000\,\mathrm{MW}$, $P_{R2} = 4000\,\mathrm{MW}$, $P_{R3} = 8000\,\mathrm{MW}$.

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